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The nature of increased cutting ability of a polyethylene oxide solution jet while processing food products

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Objective – to determine peculiarities of macromolecule deformation behaviour under conditions of a jet-shaping head that would allow to solve the issue related to the mechanism of increasing water-jet cutting power with polymer additions.

There have been studied experimentally velocity fields and their gradients as well as the degree of macromolecule unrolling under pattern conditions of a jet-shaping head in PEO solutions flow. In converging polymer solution flow macromolecules are forced by a hydrodynamic field to rather strong (up to 60 %) stretching that causes the field restructuring. The determined regularities of macromolecules behavior in the flow with longitudinal velocity gradient and manifested in this case effects of elastic deformations have paramount importance in understanding the mechanism of “anomalously” high cutting power of water-polymer jet.

Understanding the nature of increased cutting power of water-polymer jet will make it possible to develop recommendations on choosing regimes for water-polymer jet processing of foodstuffs by cutting.

Key words: polymer solution, foodstuff, polyethyleneoxide, velocity, hydrodynamic field, velocity gradient, deformation effects.

Природа повышенной режущей способности струи раствора полиэтиленоксида при обработке пищевых продуктов

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Цель – установить особенности деформационного поведения макромолекул в условиях струеформирующей головки, которые позволят подойти к решению вопроса о механизме увеличения режущей способности гидроструи с полимерными добавками.

Экспериментально изучены поля скоростей и их градиентов, а также степень развернутости макромолекул в модельных условиях струеформирующей головки при течении растворов полиэтиленоксида. При сходящемся течении раствора полимера макромолекулы подвергаются весьма сильному (до 60%) разворачиванию под действием гидродинамического поля, что

в результате приводит к перестройке структуры этого поля. Установленные закономерности поведения макромолекул при течении с продольным градиентом скорости и проявляющиеся при этом эффекты упругих деформаций имеют определяющее значение в понимании механизма «аномально» высокой режущей способности водополимерной струи.

Ключевые слова: полимерный раствор, пищевые продукты, полиэтиленоксид, скорость, гидродинамическое поле, градиент скорости, деформационные эффекты.

The experiments were conducted by us to ascertain the nature of increased cutting ability mechanism of high speed jet of polyethylene oxide (PEO) aqueous solution. The study of PEO concentration effect on cutting performance of food products frozen to minus 25°C and to the temperature of liquid nitrogen (minus 195,8°C) with hydro-polymer jet having outflow pressure of 100mpa and a nozzle diameter of $0,35 \cdot 10^{-3}$ m showed that cutting speed grows with increasing concentration of PEO in water and reaches its maximum at some optimal value. The optimal concentration equaled 0,007% for PEO molecular weight $6 \cdot 10^6$. Experiments gave an increase of high speed water jet cutting ability due to PEO additives to it by an order of magnitude while cutting meat frozen to minus 25°C and by 5 times for meat frozen to minus 195,8°C [1].

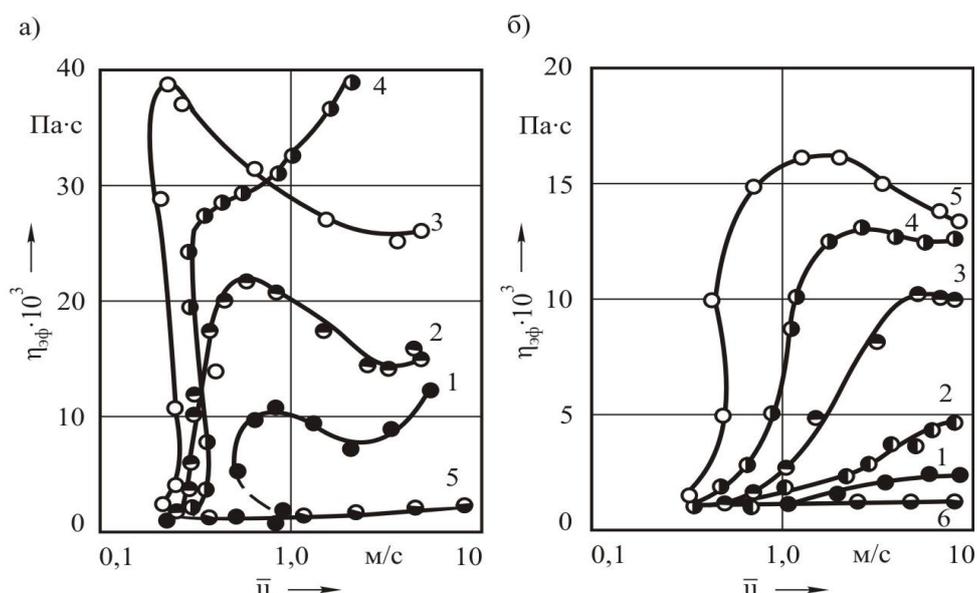
Among the attempts to explain the nature of the effect of water-polymer jet “anomalously” high cutting power a special place is held by an approach based on deformation impact of hydrodynamic field on macromolecules. To substantiate this approach it is necessary to prove experimentally the presence of strong deformation impact of hydrodynamic field under conditions of a jet-shaping head.

The research of converging currents has shown that it is possible to generate flow with predominantly longitudinal velocity gradient, i.e. to simulate conditions that appear in a jet-shaping head, with the help of a short capillary tube [2].

Data describing the influence of discharge velocity on effective viscosity of water PEO solutions with different concentrations for molecular weights of $4 \cdot 10^6$ and $6 \cdot 10^6$ at 25°C are given on fig.1.

It can be seen, that the phenomena, unusual for purely viscous mediums are characteristic of such currents. At certain critical (threshold) values of average exhaust velocity \bar{u} the relative pressure differential begins sharply to increase, and it is the sharper the more is the concentration of polymer in a solution. The marked character of dependence $\xi = f(\bar{u})$ testifies about high dissipation (sometimes, than is on 2 orders of magnitude more) of energy during the course of solutions of polymers through an slot i.e. the increased hydrodynamic resistance on supercritical flow rates is observed. Transition to a mode of current with an increased dissipation of energy is accompanied by formation of the source flooded jet as “cord” enclosed by secondary currents in the shape of a ring-shaped vortex. In case of supercritical mode of current for area of the concentration lying between very diluted and moderately concentrated solutions of polymers, there happens rather strong deformation effect of a hydrodynamic field on molecular chains.

To interpret the data, the structure of the hydrodynamic field and degree of the molecular shape distortions induced by the field should be evaluated. In this study, velocity and velocity gradient fields as well as the degree of the coil-stretch transition at the entrance of the capillary were investigated for various flow regimes.



a) $d_k = 0,34 \cdot 10^{-3}$ м, $l_k = 10^{-3}$ м, $M_{\text{PEO}} = 4 \cdot 10^6$, C_{PEO} : 1 – 0,01%, 2 – 0,02%, 3 – 0,05%, 4 – 0,1%, 5 – water;

б) $d_k = 0,12 \cdot 10^{-3}$ м, $l_k = 0,2 \cdot 10^{-3}$ м, $M_{\text{PEO}} = 6 \cdot 10^6$, C_{PEO} : 1 – 0,0005%, 2 – 0,001%, 3 – 0,002%, 4 – 0,003%, 5 – 0,004%, 6 – water

Figure 1 – Dependence of effective viscosity of water PEO solutions on average discharge velocity

A flow viscometer with an entrance angle of 180°C was used. The instrument contained a cell having a rectangular cross-section $(10 \times 17) \cdot 10^{-3}$ м and height of $8 \cdot 10^{-2}$ м and two short removable capillaries having the following diameter and length, respectively: $0.5 \cdot 10^{-3}$ and $0.21 \cdot 10^{-3}$ м (capillary I) and $0.37 \cdot 10^{-3}$ м and $1.1 \cdot 10^{-3}$ м (capillary II). The velocity field at the entrance of the capillaries was measured using a laser Doppler anemometer according to the method. The average flow rate \bar{u} was measured volumetrically using a photo-electronic system; the flow downstream the capillary inlet was submerged. PEO having the viscosity-average molecular weight of $M_\eta = 4 \cdot 10^6$ was used as a polymeric additive. The solutions were prepared in the following manner. A previously (one week before) prepared 0.1% solution of PEO was diluted with distilled water. Additives of 0.05% potassium iodide were introduced to exclude degradation of the polymer solutions upon storing [2–4].

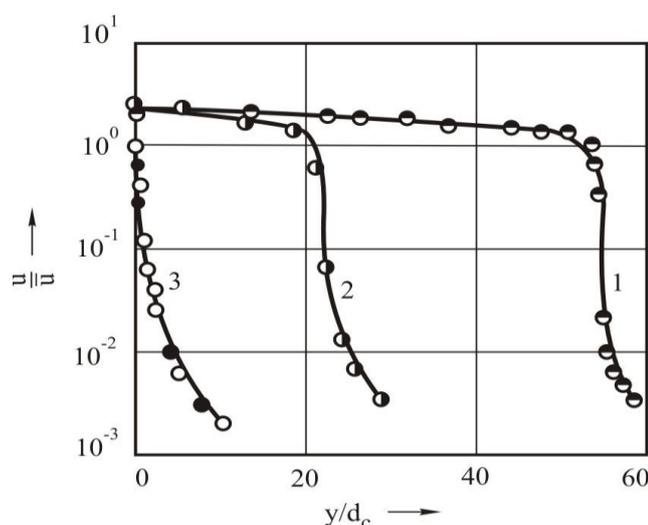


Figure 2 – Velocity distribution for the polymer solution along the flow axis

Flow through the capillary I at the average flow rate $\bar{u} = 2.5 \text{ m} \cdot \text{s}^{-1}$ (1), flow through the capillary II at $\bar{u} = 0.8 \text{ m} \cdot \text{s}^{-1}$ (2) and through the capillary II at $\bar{u} = 0.5 \text{ m} \cdot \text{s}^{-1}$ (3).

Filled circles represent the data for water when $\bar{u} = 0.8 \text{ m} \cdot \text{s}^{-1}$

Distribution of the flow rate along the flow axis for 0,05% PEO solution in dimensionless coordinates is depicted in Figure 2.

It can be seen that, before the critical flow regime is attained, the anti-thixotropic increase of the effective viscosity is not exhibited and the axial distributions of velocity for the polymeric solution and pure water are almost the same (curve 3) and filled circles on curve 3, respectively. After passing through the critical flow regime, the curves exhibit a considerable deformation and development of the axial velocity profile (curves 1 and 2 in Figure 2). The latter curves have at least two linear regions. It should be pointed out that after passing through the critical threshold, the flow velocities of the polymeric solutions exhibit considerable fluctuations, exceeding one order of magnitude. The range of fluctuations is dependent on the average flow rate, the diameter of the capillary, the molecular weight of the polymer, its concentration, its temperature, as well as its distance from the capillary inlet.

Step-by-step playback of a video recording of the flow demonstrated that the fluctuations were associated with periodical formation and breakdown of the vortex upstream of the capillary inlet; the breakdown may be partial or complete. The changes with time in the hydrodynamic field correlate with the velocity changes; thus, the maximal rate at the flow axis is attained when the maximal length of the vortex is attained. The moment when the vortex has developed to its final shape seems to be the most interesting, since the largest degree of the coil-stretch transition of polymer can be expected in that state. Hence, when studying the axial distributions of velocity, only the maximal values arising at different average flow rates through the capillary were taken into account. A comparison of the velocity distributions along the flow axis with the corresponding patterns of streamlines allows the conclusion to be drawn that the steep decrease in the velocity occurs at the entrance zone of the vortex.

Using the experimental velocity distributions along the flow axis, the respective rate gradient distributions were calculated (Figure 3).

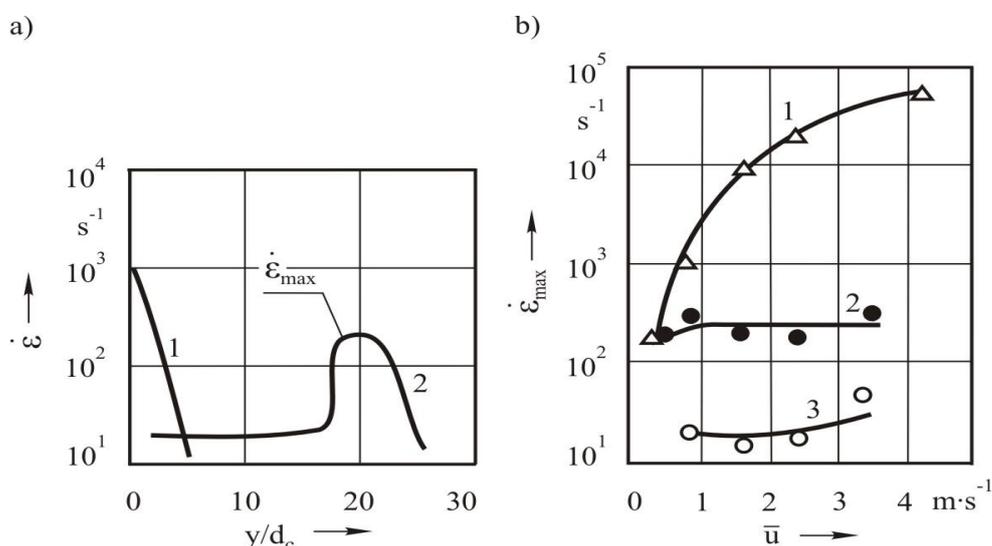


Figure 3 — (a) – Velocity gradient distribution along the flow axis at $\bar{u} = 0.8 \text{ m} \cdot \text{s}^{-1}$ for water (1) and 0.05% PEO solution (2)

Measurements were performed with the capillary I; **(b) – Dependence of the maximal longitudinal velocity gradient on the average flow rate for water (1) and 0.05% PEO solution (2) and $\dot{\epsilon}$ in the vortex for 0.05% PEO solution (3).**

Measurements were performed with the capillary I

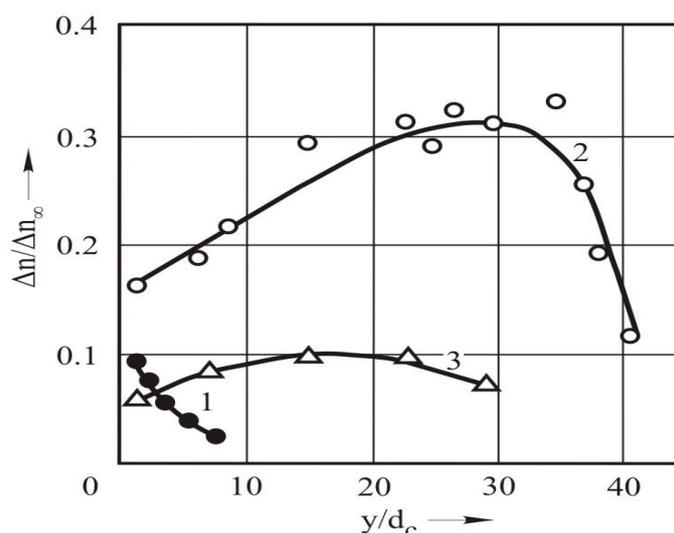
It can be seen that the maximal rate gradient $\dot{\epsilon}_{\max}$, occurs not at the entrance of the capillary, but at some distance from that point equal to the length of the vortex (Figure 3,a, curve 2). The $\dot{\epsilon}_{\max}$ at the entrance of the

capillary for polymeric solution is considerably lower than that for water. Hence, the hydrodynamic field results in perturbation of the macromolecules, which, in turn, affects the velocity field in such a way that the longitudinal velocity gradients are decreased. Thus, the longitudinal velocity gradient at the vortex axis does not exceed 30 s^{-1} . An increase in molecular weight of the polymer and its concentration also results in decrease of the longitudinal gradient at the vortex axis. Thus, the respective value for 0.2% PEO solution and capillary I at the average flow rate $2 \text{ m} \cdot \text{s}^{-1}$ is equal to 10 s^{-1} . Such low values were also confirmed by the streak photography method. The photographs of the tracks of particles envisage that distances between the particles' positions assumed between the equal time gaps are almost the same, which confirms that the velocity gradient at the vortex axis is close to zero.

Figure 3,b illustrates that the longitudinal rate gradient at the axis of the vortex (curve 3) and maximal value of the rate gradient at the entrance of the capillary (curve 2) are only slightly dependent on the average flow rate through the capillary.

Hence, a novel method of controlling the flow of polymeric solutions has been found. Indeed, the structure of hydrodynamic field of a Newtonian fluid at a given value of the flow rate is strictly determined by the shape of the walls of the flow element and the average flow rate, whereas in our case the polymeric solution itself “regulates” the flow structure, which turns out to be absolutely independent (in classical sense) of the configuration of the walls.

The observed changes in the structure of the hydrodynamic field can be associated with large distortions of the macromolecular coils induced by hydrodynamic field, leading to non-linear elasticity effects. The degree of the coil-stretch transition may be estimated from the value of the deformational factor $\frac{\Delta n}{\Delta n_{\infty}}$, where Δn is the experimental flow birefringence value, while the Δn_{∞} is the limiting value of the flow birefringence calculated at the given concentration of polymer. The methods of Δn_{∞} calculations and experimental procedure of Δn measurements are given elsewhere [5].



$C_{\text{PEO}} = 0.3\%$ (1), $\bar{u} = 1 \text{ m} \cdot \text{s}^{-1}$; $C_{\text{PEO}} = 0.03\%$ (2), $\bar{u} = 2.5 \text{ m} \cdot \text{s}^{-1}$;

$C_{\text{PEO}} = 0.1\%$ (3), $\bar{u} = 1 \text{ m} \cdot \text{s}^{-1}$. Measurements were performed with the capillary I

Figure 4 – The distribution of the coil-stretch transition degree over distance from the entrance of the capillary for aqueous PEO solution

Results of the studies of the influence of hydrodynamic field on the polymeric solution are depicted in Figure 4. The value of deformational factor increases when approaching the entrance of the capillary for the

average flow rate equal to the critical value (curve 1) and reaches its maximum at rather high \bar{u} values (curve 2). The maximum position of the deformational factor $\frac{\Delta n}{\Delta n_\infty}$, at the entrance of the capillary corresponds to the domain with maximal longitudinal velocity gradient (Figure 3,a, curve 2).

As mentioned previously, the flow becomes rather unstable after passing through the critical threshold, which can be seen from the plot of the laser beam intensity vs. time in Figure 5,a (the laser beam crossed the flow axis above the capillary entrance at the distance equal to the diameter of the capillary). The fluctuations are accompanied by the flow birefringence at the capillary inlet. Hence, during the flow birefringence measurements, only maximal Δn values at the given average flow rate of polymeric solution have been taken into consideration, as in the case of the velocity measurements.

The obtained distribution of the deformational factor over the flow axis at the entrance of the capillary (Figure 4) envisages the possibility of a high degree of coil-stretch transition under the free-converging flow conditions. The flow birefringence ratio attains the value of 0.33, which corresponds to ~60% coil-stretch transition degree. Increasing the polymer concentration results in a decrease of the deformational factor (curve 3). Thus, for a 0.1% PEO solution characterized by the $[\eta]_0 C_{PEO} = 1.72$, the $\frac{\Delta n}{\Delta n_\infty}$ ratio is equal to 0.1. Hence, in moderately concentrated (semi-dilute) solutions, the coil-stretch transition degree attains 30% [2, 3, 5–7].

Figure 5 envisages deformational behavior of macromolecules at the different flow rates. It can be seen that the $\left(\frac{\Delta n}{\Delta n_\infty}\right)_{\max}$, vs. average flow rate dependence may be divided onto three domains. Domains 1 and 3 are characterized by a monotonic increase of the coil size with growth of the flow rate, while in the intermediate domain 2 the transition is rather sharp. From a comparison of Figures 3 and 5, it can be concluded that an increase of the \bar{u} in the domain I is accompanied by growth of the longitudinal velocity gradient, which results in an increase of the size of the coils.

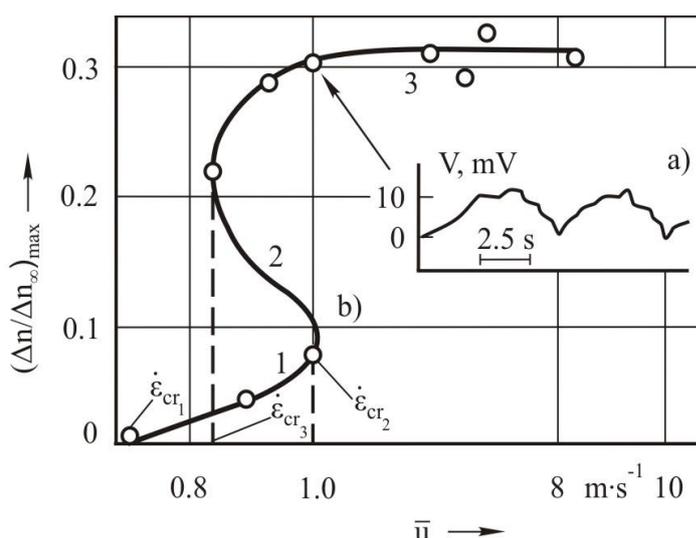


Figure 5 – Fluctuations with time of the laser intensity (a) and dependence of the coil-stretch transition degree on average flow rate (b). Measurements were performed with the capillary I and 0.03% PEO solution. The arrow marks the flow regime corresponding to the (a) plot of the laser intensity fluctuations

The values of the rate gradients arising at the entrance of the capillary for polymeric solutions are somewhat lower than those for water at the same average flow rate. When attaining some critical velocity

gradient $\dot{\epsilon}_{cr2}$, a sharp transformation of the size of the coils occurs. The sharp jump of the deformational factor with an increase of the average flow rate is an indication that the hydrodynamic field results in conformational instability of the macromolecules and the occurring coil-stretch transition is the first order phase transition. The phase transition results in a considerable readjustment of the velocity field leading to decrease of the longitudinal gradient which takes on the value $\dot{\epsilon}_{cr3}$; the latter, however, must remain greater than $\dot{\epsilon}_{cr1}$, which is the rate gradient when the flow birefringence zone is arising at the entrance of the capillary, i.e., the $\dot{\epsilon}_{cr1} < \dot{\epsilon}_{cr3} < \dot{\epsilon}_{cr2}$ condition must hold. A further increase of \bar{u} only slightly affects the deformational factor and the value of longitudinal gradient, see the domain 3. In that domain, considerable changes in velocity result in only slight variations of the longitudinal gradient (Figure 3,b, curve 2); this fact proves the non-linear dependence of the stretching degree on the rate gradient. According to Nikolis and Prigozhin [8], at least, the cubic non-linearity must occur.

The experimental data presented above clearly demonstrates that the water-polymer system under appropriate conditions of the converging flow exhibits self-organization with the negative feedback coupling. Indeed, increase of the longitudinal rate gradient results in the coil-stretch transition of the polymers, which, in turn, affects the flow structure in such a way that the longitudinal gradients become smaller. The gradients must remain greater than some critical value sufficient for the coil stretching, which is related to the macromolecule relaxation time θ by the following formula: $\theta \cdot \dot{\epsilon}_{cr} = 0.5$ [9]. Otherwise, the reverse stretch-coil transition occurs [10] and macromolecules decrease their influence on the velocity field, which, in turn, results in a steep increase of the velocity gradient. This will lead to the coil-stretch transition and all the above processes will happen once again. Hence, the stable state is characterized by the minimal value of the velocity gradient which is sufficient for a sharp coil-stretch transition. Increase in the flow rate results in some additional growth of the deformational factor due to nonlinear effects (Figure 5, domain 3) sufficient for stability of the rate gradient field of the chosen polymeric system (Figure 3(b), curve 2).

Hence, peculiarities of the free-converging flow of the polymeric solutions are associated with a high degree (~60%) of reversible stretching of macromolecules caused by the hydrodynamic field and with an influence of the stretched macromolecules on the structure of the field. The determined regularities of macromolecules behavior in the flow with longitudinal velocity gradient and manifested in this case effects of elastic deformations have paramount importance in understanding the mechanism of “anomalously” high cutting power of water-polymer jet processing of foodstuffs by cutting.

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